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Quantitative Ultrasonic Multilayer Characterization for Integration Monitoring of Hip Implants

J. Lützelberger[1] *and K.S. Drese*[1]
[1]*Coburg University of Applied Sciences and Arts, ISAT - Institute of Sensor and Actuator Technology, Coburg, Bavaria, Germany*
jan.luetzelberger@hs-coburg.de

Abstract: New quantitative data processing methods could enable ultrasound as a potential diagnostic method for hip implant integration monitoring. For development of such methods, suitable acoustic simulation tools are essential. In this work, a novel 1D FDTD simulation tool for multilayer structures, considering frequency-dependent properties, is introduced, particularly meeting the special needs of this application. Simulation results show excellent agreement with experimental data, confirming accurate prediction of wave propagation in multilayer systems.

Keywords: Ultrasound simulation, Finite-Difference Time Domain (FDTD) simulation, Quantitative Ultrasound (QUS), Hip prostheses, Multilayer systems

Introduction

Model-based ultrasonic methods for characterizing multilayer structures with thin interlayers are well-known in industrial applications, such as non-destructive testing of adhesive bonds [1]. In medicine, quantitative ultrasonic (QUS) methods for tissue characterization are gaining importance too [2]. However, many anatomical structures are multilayer systems, leading to multiple transmission and reflection effects. This complicates understanding sound propagation and developing suitable data processing methods for analyzing such structures. One example is the multilayer-like structure in the thigh of patients with hip prostheses, consisting of soft tissue, bone, a mm- to sub-mm-thin bone-implant interlayer, and the implant [3]. Determining thicknesses and material properties of these layers could enable a quantitative implant integration monitoring and early detection of pathological changes like implant loosening [4, 5].

The properties of each layer which are relevant for implant integration quality (thicknesses, sound velocity, sound impedances, attenuation coefficients) can vary in large ranges [6], so it is not possible to capture all configurations within experiments. Simulation studies are therefore essential to identify the relevant configurations for experimental evaluation of new data processing algorithms. Furthermore, they enable visualization and therefore deeper understanding of sound propagation within the layered system itself, while, in experimental analysis, ultrasonic transducers can only detect signals at the outer layers of the system. Consequently, they play an important role in the actual development of new data processing methods too.

A suitable simulation tool for modeling longitudinal ultrasound propagation in complex multilayer structures has to fulfill several requirements: the possibility to model any desired multilayer system (various thicknesses and acoustic properties per layer), support of any number of layers, representation of frequency-dependent attenuation, inclusion of multiple reflection and transmission processes at each layer boundary, support of any excitation pulse frequency and shape and visualization of the resulting wave field at any time and location within the simulation area.

Well-known acoustic simulation tools for industrial and medical purposes mainly include Field II [7], SimSonic [8], k-Wave [9] and COMSOL Multiphysics [10]. While Field II does not support multiple layers with different properties, SimSonic fails to model more complex attenuation patterns. MATLAB-based k-Wave and COMSOL Multiphysics meet these requirements but rely on commercial licenses.

This publication now introduces a novel, Python-based and therefore completely open-source simulation tool for ultrasonic propagation through multilayer structures, particularly addressing the special requirements stated above. It currently works for one dimension and parallel layers, but can potentially be extended to more spatial dimensions. The basic principles of the simulation tool are described as well as results from a comparison with experimental data.

While this paper focuses on this new simulation tool enabling the development of new multilayer characterization methods, novel data processing procedures themselves will be presented in future publications.

Materials and Methods

The presented simulation tool is based on a Finite-Difference Time Domain (FDTD) approximation of the linear transport equations in $-x$- and $+x$-

direction, respectively,

$$\frac{\partial \sigma}{\partial x} = \pm \frac{1}{c} \frac{\partial \sigma}{\partial t} \tag{1}$$

where σ represents the propagating sound field quantity (e. g. mechanical stress) propagating in $\mp x$-direction through time t with sound velocity c. By using two linear transport equations instead of one wave equation which combines both of them, sound propagation in each direction can be visualized separately, enhancing clarity of the simulation results. Within one layer, the transport equations are discretized using explicit Lax-Wendroff method

$$\frac{\sigma_r^{p+1} - \sigma_r^p}{\delta t} = \pm c \frac{\sigma_{r+1/2}^{p+1/2} - \sigma_{r-1/2}^{p+1/2}}{\delta x} \tag{2}$$

of $\mathcal{O}(\delta x^2, \delta t^2)$ to reduce numerical dissipation and enhance accuracy. At the layer boundaries, Upwind discretization with

$$\frac{\sigma_r^{p+1} - \sigma_r^p}{\delta t} = \pm c \frac{\sigma_{r+1}^{p} - \sigma_{r}^{p}}{\delta x} \tag{3}$$

was used to calculate the wave field σ_r^{p+1} at the next time step t_{p+1}. r and p indicate the current space and time step x_r and t_p, while δx and δt represent the space and time increments. Given one of them, the other one results from the well-known CFL condition by taking the system's highest sound velocity.
Fig. 1 illustrates how the simulation area is built by

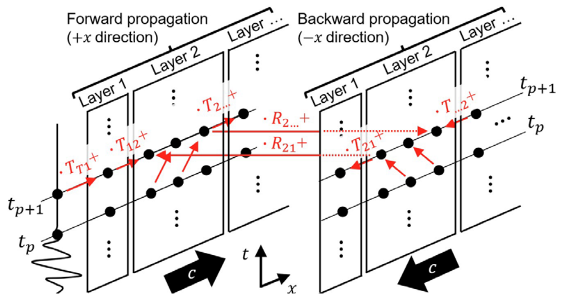

Fig. 1: Schematic drawing of the simulation area and the principle of calculating the next time step t_{p+1}.

one matrix per layer and propagation direction. Using Eq. (2), σ_r^{p+1} is computed for each point inside a layer. Correct reflection and transmission behavior is applied by first calculating the wave field at each boundary point using Eq. (3) and then multiplying with the associated reflection or transmission coefficient calculated from the respective acoustic impedances by

$$R_{ij} = \frac{Z_j - Z_i}{Z_i + Z_j}; \; T_{ij} = \frac{2\, Z_j}{Z_i + Z_j} \tag{4}$$

as Fig. 1 shows too. i and j indicate the previous and next layer according to the propagation direction.

Frequency-dependent attenuation is modeled by a Fourier decomposition of the excitation signal as shown in Fig. 2. After decomposition, one simula-

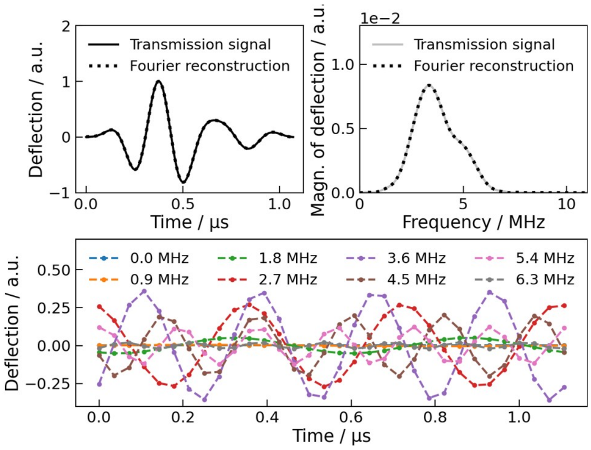

Fig. 2: Spectral decomposition by Fourier expansion for exemplary excitation signal.

tion with the associated monofrequent oscillation (see Fig. 2) for each Fourier coefficient as input signal is performed. In every time step, the resulting deflection is reduced by the attenuation value for this specified frequency. Finally, a summation of simulated wave fields for all frequencies gives the wave field for the actual broadband excitation signal.
As input parameters, the simulation tool needs thickness, sound velocity, acoustic impedance, attenuation coefficient and attenuation exponent for each layer as well as the desired spatial increment, total simulation time and excitation signal.

Results

Tab. 1 shows the relevant properties of an exemplary

Tab. 1: Properties of each layer of the exemplary multilayer system the simulation tool was tested with.

Layer	Thickness mm	Sound velocity m/s	Acoustic impedance MNs/m^3	Attenuation coefficient dB/(cm MHz)
1	8.5	1465	1.230	0.530
2	4.2	3376	6.840	3.960
3	–	1483	1.479	0.002
4	21	6112	26.97	0.246

multilayer system consisting of a flexible acoustic coupling mat (layer 1), a cortical bone plate (layer 2), a water gap of variable thickness (layer 3) and a titanium plate (layer 4). The attenuation exponent was

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set to 1 for all layers. The acoustic properties of these materials were determined by puls-echo measurements and evaluation of the multiple reflections within the material probes in time and frequency domain using an immersion transducer (C384-SU, Evident Corporation, Tokyo, Japan). This multilayer system artificially represents the acoustic path at a thigh with hip prosthesis. As different thicknesses of the water interlayer represent different prosthesis integration or loosening states, evaluation of those plays an important role for implant integration monitoring.
Fig. 3 now shows the simulated wave field at different

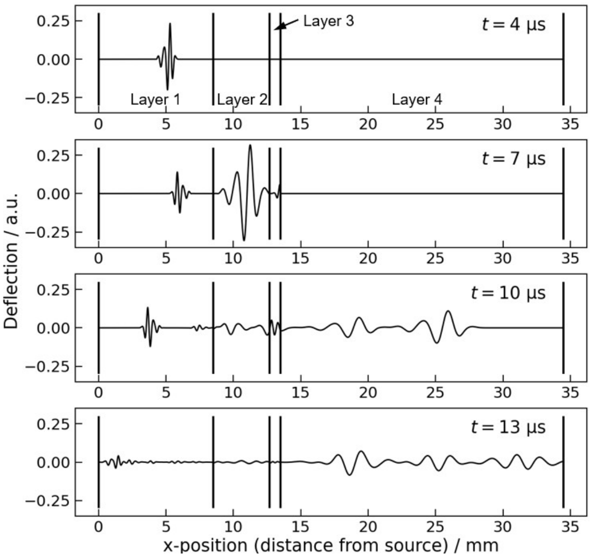

Fig. 3: Simulated wave fields at different points in time after excitation for a multilayer system with properties listed in Tab. 1, water gap thickness of $h_3 = 800\,\mu m$ and $\delta x = 5\,\mu m$. Each vertical line represents a layer boundary.

times for this multilayer system using an excitation signal as produced by the C384-SU transducer and already shown in Fig. 2. Several transmission and reflection effects are visible, including amplitude changes and different wavelengths across the various layers.
For evaluating the accuracy of the simulation tool by comparing with experimental data, a similar measurement setup as in [5] with the same measurement devices including the C384-SU transducer in pulse-echo mode but with the layer materials stated above was used. Fig. 4 shows the simulated wave field at $x = 0\,\mu\text{m}$, i. e. the received signal in pulse-echo mode, and the experimentally determined signal as well. Both signals show good agreement in shapes and amplitudes, except for the parts marked with numbers.
The signal range where the interlayer reflections occur is marked with a rectangular box as it contains the most relevant information for implant integration mon-

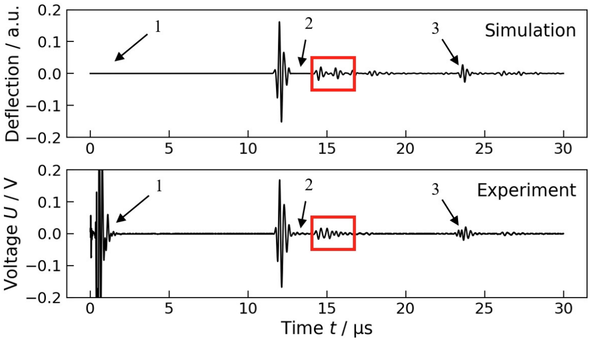

Fig. 4: Simulated and measured received signals for the same multilayer system as in Fig. 3 at $x = 0\,\mu m$. Deviating signal effects are marked by numbers.

itoring. For this signal part, Fig. 5 directly compares

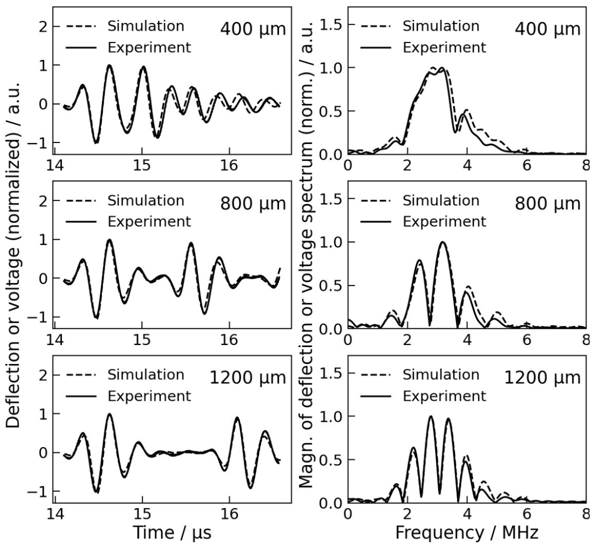

Fig. 5: Comparison of simulated and measured received signal within the interlayer reflection range (rectangular box in Fig. 4) for three different water gap thicknesses in time and frequency domain.

simulated and measured reflection signals for three different water gap thicknesses in time and frequency domain. The latter is shown because the frequency domain is especially suitable for determining small interlayer thicknesses [5]. For all three thicknesses, simulation and experiment agree almost completely, with slight deviations especially a higher frequencies.

Discussion

The comparison of the resulting wave fields from the presented simulation tool with experimental data shows a very good overall agreement, both for the total received signal and the interlayer reflection interval as the main region of interest.

Within the total received signal (see Fig. 4), the experimental effect at marking 1 is related to electrical crosstalk due to the electrical switch used to perform transmission and reception with one and the same transducer. The small oscillations in the experimental signal at marking 2 point to scattering within the bone plate which is not captured by the simulation tool. Finally, the additional reflection effect in the experimental signal at marking 3 is caused be multiple reflections inside the transducer's matching layer which is also not part of the simulation model.
For the interlayer reflection interval (see Fig. 5), the small deviations in time and frequency domain may result from scattering effects that are not included in the simulation model and overlay with the reflections at the interlayer boundaries or deviations in the actual water gap thickness within the experimental setup caused by not exactly plane-parallel surfaces.
Overall, the developed simulation tool fully meets the initially stated requirements and is therefore suitable for assisting in developing new ultrasonic data processing algorithms for an hip implant integration monitoring. Nevertheless, it does not address several sound propagation aspects that could also be relevant for the actual application, like curved surfaces with refraction, heterogeneous and porous structures with anisotropic and scattering effects or the sound field geometry of real ultrasonic transducers. For such simulation tasks, one has to use more complex simulation tools like FEM-based COMSOL Multiphysics or k-Wave which is based on a pseudo-spectral method.

Conclusion

A novel FDTD simulation tool for 1D wave propagation in multilayer systems was introduced. It especially takes account for frequency-dependent attenuation and arbitrary properties of any number of layers. A comparison with pulse-echo data from an experimental multilayer system showed very good agreement and high accuracy of the simulation results. Next steps include expanding the tool to two spatial dimensions and including other propagation effects like refraction, scattering and anisotropic material properties.

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